Late Triassic tectonic inversion in the upper Yangtze Block: insights from detrital zircon U–Pb geochronology from southwestern Sichuan Basin

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ABSTRACT

The Sichuan Basin and the Songpan-Ganze terrane, separated by the Longmen Shan fold-and-thrust belt (the eastern margin of the Tibetan Plateau), are two main Triassic depositional centers, south of the Qinling-Dabie orogen. During the Middle – Late Triassic closure of the Paleo-Tethys Ocean the Sichuan Basin region, located at the western margin of the Yangtze Block, transitioned from a passive continental margin into a foreland basin. In the meantime, the Songpan-Granze terrane evolved from a marine turbidite basin into a fold-and-thrust belt. To understand if and how the regional sediment routing system adjusted to these tectonic changes, we monitored sediment provenance primarily by using detrital zircon U-Pb analyses of representative stratigraphic samples from the southwestern edge of the Sichuan Basin. Integration of the results with paleocurrent and published detrital zircon data from other parts of the basin identified a marked change in provenance. Early-Middle Triassic samples were dominated by Neoproterozoic (~700-900Ma) zircons sourced mainly from the northern Kangdian basement, whereas Late Triassic sandstones recorded a more diverse range of zircon ages, sourced from the Qinling, Longmen Shan and Songpan-Ganze terrane. This change reflects a major drainage adjustment in response to the Late Triassic closure of the Paleo-Tethys Ocean and significant

shortening in the Longmen Shan thrust belt and the eastern Songpan-Ganze terrane. Further, by Late Triassic time, the uplifted northern Kangdian basement had subsided. Considering the eastward paleocurrent and depocenter geometry of the Upper Triassic deposits, subsidence of the northern Kangdian basement probably resulted from eastward shortening and loading of the Songpan-Ganze terrane over the western margin of the Yangtze Block in response to the Late Triassic collision between Yangtze Block, Yidun arc and Qiangtang terrane along the Ganze-Litang and Jinshajiang sutures.

INTRODUCTION

The Sichuan Basin, located along the western margin of the Yangtze Block, shares common borders with five major tectonic terrains: (1) Qinling-Dabie orogen to the north, (2) the Songpan-Ganze terrane (i.e. the eastern Tibetan Plateau) to the northwest, (3) the Yidun arc to the west, (4) Kangdian Basement to the south and (5) the eastern Sichuan fold-and-thrust belt to the east (Fig. 1). Numerous structural, geochronological, and sedimentary studies suggested that these areas had experienced a significant phase of crustal shortening and rock exhumation during Triassic closure of the Paleo-Tethys Ocean (Burchfiel *et al*., 1995; Zhang *et al*., 1995; Yin, 1996; Meng & Zhang, 2000; Li *et al*., 2003a; Wang *et al*., 2005; Jia *et al*., 2006), and that tectonic loading over the margins Sichuan Basin changed the setting from a passive continental margin to a foreland basin.

In the context of these changes, the provenance of sediments deposited in the Sichuan Basin have seen extensive study, much based on detrital zircon U-Pb geochronology (Deng *et al*., 2008; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015a; Li *et al*., 2016; Shao *et al*., 2016; Zhu *et al*., 2017). Results from previous work suggest that sediments in the basin were mainly sourced from the Qinling-Dabie orogen, to the north, and the Longmen Shan thrust belt and the Songpan-Ganze terrane to the west. However, most of those previous studies focused on the Late Triassic - Cretaceous foreland basin sediments in the western and northern part of the Sichuan Basin (Fig. 1). The provenance of Early and Middle Triassic passive continental margin deposits is unknown. Constraining the provenance of sediments deposited before and after Late Triassic inversion of the Sichuan Basin could provide significant insights into whether the sediment routing system into the basin had significantly changed.

Previous sedimentary and stratigraphic studies showed that the Early – Middle Triassic paleogeography is characterized by a lateral facies transition from clastic to carbonate away from the southern edge of the basin to the interior (Liu & Tong, 2001; Long *et al*., 2011; Zhao *et al*., 2012; Tan *et al*., 2014; Wei *et al*., 2014), indicating that the southwestern basin margin was bounded and sourced by a highland to the south. The highland consists of Neoproterozoic basement and is referred to as the Kangdian basement (referred to the Kangdian Oldland or Kangdian Axis by Chinese researchers) (Li, 1963; Luo, 1983; Wang *et al*., 1983; Dai *et al*., 2012; Tan *et al*., 2013) (Fig. 1). However, in response to closure of the Paleo-Tethys Ocean, the entire basin transitioned into a foreland basin with detritus sourced mainly from the Longmen Shan thrust belt and the Qinling-Dabie orogen to the west and north of the basin. These earlier sedimentary studies imply a significant change in sediment provenance during Late Triassic basin inversion. To test this we applied detrital zircon geochronology to a series of Early-Late Triassic sandstone samples collected from the southwestern part of the Sichuan Basin. Depositional ages of sampled rocks are constrained by new zircon U-Pb results derived from a newly mapped volcanic tuff. The results are interpreted together with previously mapped stratigraphic correlations and paleocurrent data, in order to constrain the paleogeographic evolution of the southwestern margin of the Sichuan Basin during Early-Late Triassic time, and to test if and how crustal shortening and rock uplift during the Triassic had influenced sedimentary routing network across the basin margin.

GEOLOGICAL SETTING

The southwestern part of the Sichuan Basin is bounded by the Kangdian basement uplift to the south and the Songpan-Ganze terrane and Longmen Shan to the west (Figs 1, 2). The Triassic and Cenozoic geological evolution of these major terranes is summarized below.

Regional Tectonism

Triassic evolution of the Sichuan Basin and surrounding regions was controlled by the Middle - Late Triassic closure of the Paleo-Tethys Ocean along the Mianlue suture, forming the Qinling-Dabie orogen (e.g. Zhang, *et al.*, 1995; Yin, 1996; Meng, & Zhang, 2000; Li, *et al.*, 2003a), and the Litang and Jinshajiang sutures north and south of the Yidun arc (Fig. 1, e.g. Reid *et al.*, 2005; Roger *et al.*, 2008; Pullen *et al.*, 2008; Roger *et al.*, 2010; Yuan *et al.*, 2010; Wang *et al.*, 2013a). During this time basin margins, especially the Longmen Shan and Songpan-Ganze turbidite terrane to the west, were significantly shortened (e.g. Huang *et al.*, 2003; Yan *et al.*, 2011; Weller *et al.*, 2013; Zheng *et al.*, 2016), inducing several kilometers of flexural subsidence (e.g. Guo *et al.*, 1996; Li, *et al.*, 2003a; Meng *et al.*, 2005). By the Cenozoic basin margins were reactivated by the Indo-Asian collision and the subsequent outward growth of the Tibetan Plateau (Enkelmann et al., 2006; Liu-Zeng *et al.*, 2008; Wang *et al.*, 2012a; Tian *et al.*, 2012, 2013).

Sichuan Basin

Phanerozoic evolution of the Sichuan Basin can be divided into three major stages: a passive margin stage characterized by platform carbonates during Paleozoic to Middle Triassic time (Xu *et al.*, 1997), a Late Triassic foreland basin characterized predominantly by continental siliciclastic sedimentation (Li *et al.*, 2003a), and a prolonged phase of denudation in the eastern and central Sichuan Basin since the Late Cretaceous, as shown by thermochronological studies (Tian *et al.*, 2012; Yang et al., 2017). In this study, we focus on the provenance of the Triassic detritus in the southwest Sichuan Basin that consists of, from bottom to top, the Feixianguan, Jialingjiang, Leikoupo, Maantang, Xiaotangzi and Xujiahe Formations, (Fig. 3).

(1) The marine Feixianguan Formation is widely distributed in the Sichuan Basin and shows marked lateral lithofacies variations. The formation consists of purple shale and sandy shale, interbedded with grey limestone, oolitic limestone, marl and sandstone in western parts of the basin, which changes into limestone toward the eastern basin (BGMRSP, 1997). The biostratigraphic age of the formation is earliest Triassic (BGMRSP, 1997) , ~252 Ma supported by zircon U-Pb ages from volcanic ash beds at the bottom of the formation (Burgess *et al.*, 2014). The isopach map of this formation shows a depocenter located in the center of the basin (Fig. 4c).

(2) The marine Jialingjiang Formation conformably overlies the Feixianguan Formation, and is mainly composed of limestone and dolomite (BGMRSP, 1997). In the formation, Late-Early Triassic

bivalves, ammonites, foraminiferas and conodonts have been discovered (BGMRSP, 1997). The top of the formation is marked by a widespread thin layer (the thickness is 10s cm – 1 m) of altered tuff (named as "green-bean rocks" in early Chinese literature) (Zhu & Wang, 1986), that has been dated as ~247 Ma by ID-TIMS, LA-ICP-MS and CA-TIMS on zircon (Ovtcharova *et al*., 2006; Xie *et al*., 2013; Lehrmann *et al*., 2015).

(3) The marine Leikoupo Formation mainly consists of dolomite and argillaceous dolomite, interbedded with limestone and gypsum layers (BGMRSP, 1997). It contains Middle Triassic bivalves and ammonites such as *Progonoceratites, Beyrichites* (BGMRSP, 1997). The boundary between the Leikoupo and underlying Jialingjiang Formations is marked by an altered tuff. The isopach map of this formation shows a depocenter located in the center of the Sichuan Basin (Fig. 4b).

(4) The marine Maantang Formation, distributed in the western Sichuan Basin, mainly consists of marine black mudstone and shale interbedded with siltstone, marl, oolitic and bioclastic limestones and sponge reefs (BGMRSP, 1997; Li *et al*., 2003a). It is regarded as Carnian in age on the basis of its fossil content (Shi *et al*., 2016). The Kuahongdong Formation represents equivalent coeval strata along the southwestern margin of the basin, and is composed of conglomerate, mudstone, argillaceous limestone and argillaceous dolomite (BGMRSP, 1997).

(5) The Xiaotangzi Formation, is composed of black marine shale, mudstone, quartz arenite, lithic arenite and siltstone, and can be divided into three parts: a lower part composed of black shale interbedded with quartz arenite, a middle part composed of lithic arenite and black shale, and an upper part composed of arkose. The formation coarsens upwards and is thought to represent a transition from marine shelf to delta environments. It has an early Norian age based on its fossil content (Li *et al*., 2003a).

(6) The Xujiahe Formation conformably overlies the Xiaotangzi Formation in the western Sichuan Basin, and unconformably overlies Middle Triassic limestone of the Leikoupo Formation in the central and eastern Sichuan Basin. Widely distributed, the lithology and facies of this formation changes from coarse-grained sediments, including alluvial conglomerates along the front of the Longmen Shan thrust belt, to fine-grained lacustrine deposits in the basin interior. Two depocenters developed, one in front of the central segment of the Longmen Shan thrust belt and the other in areas to the south (Fig. 4a). Depositional age of the formation is late Norian to Rhaetian based on the fossil content (WGCMSPISB, 1984; Li *et al*., 2003a).

Previous sedimentary studies suggested that the clastic deposits of the Feixianguan, Jialingjiang and Leikoupo Formations in the southwestern margin of the Sichuan Basin were sourced from the south, as shown by a facies transition from clastic to carbonate deposits from the margin to the interior of the basin (Feng *et al*., 1997; Tan *et al*., 2014; Sun *et al*., 2015). The Kangdian basement might be the source of Upper Triassic sediments, as suggested by studies on the detrital mineral assemblage, sedimentary system and conglomerate composition (Xie *et al*., 2006; Jiang *et al*., 2007; Shi *et al*., 2010). However, nonmarine Late Triassic sediments unconformably overlie the Kangdian basement (BGMRSP, 1991) indicating that the region was likely an area of deposition rather than erosion (Liu & Tong, 2001; Wei *et al*., 2014).

Kangdian Basement

The Kangdian basement forms the western margin of the Yangtze Block and extends for over 700 km from the city of Kangding in the north to the city of Yuanmou in the south (Zhou *et al*., 2002; Zhu *et al*., 2011). It is located on the western margin of the Yangtze Block (Fig. 1), and mainly consists of

Neoproterozoic basement, overlain by marine Paleozoic cover and locally by Late Triassic to Cenozoic terrestrial sediments (BGMRSP, 1991). The U-Pb age of basement has been dated as ~740–870 Ma (Li *et al*., 2003b; Zhao & Zhou, 2007; Sun *et al*., 2009).

There is a debate on the Paleozoic and Mesozoic paleogeography of Kangdian area. One model depicts the Kangdian area as a region of erosion between the Ordovician and Carboniferous (Li, 1963), followed by a rift subsidence stage from Late Permian to Jurassic (Luo, 1983; Guo *et al*., 1996). Alternately, the Paleozoic - Mesozoic geological evolution of the region can be divided into three stages: a stable marine platform from the Cambrian to Early Permian, an uplift stage affected by Emeishan mantle plume from Late Permian to Middle Triassic, and transtensional subsidence during the Late Triassic and Jurassic (Chen *et al*., 1987; Feng *et al*., 1994; Wang *et al*., 1994; He *et al*., 2003; Chen *et al*., 2011).

Longmen Shan thrust belt

The Longmen Shan is approximately >500km long and 30 - 50km wide, and defines the eastern margin of the Tibetan Plateau. It separates the strongly folded and faulted Songpan-Ganze terrane to the west from weakly deformed Sichuan Basin rocks to the east (Fig. 1). Outcrops in the Longmen Shan are mostly Neoproterozoic basement and overlying Paleozoic sedimentary strata. Zircon U-Pb analyses of Neoproterozoic basement rocks yielded ages mainly between 770-890 Ma (Fu *et al*., 2013), comparable to the age of Kangdian basement rocks, which also share similar petrology.

The Longmen Shan thrust belt experienced three phases of crustal shortening in the Early Mesozoic and Late Cenozoic. Various lines of geochronological and structural evidence have been reported for the Late Triassic formation of the Longmen Shan thrust belt (Huang *et al*., 2003; Yan *et al*., 2011; Weller *et al*., 2013), including (i) Late Triassic Barrovian metamorphism recorded by monazite U–Th–Pb and garnet Sm–Nd ages (204-190 Ma), derived from metamorphosed rocks in the Danba Antiform, immediately south of the Longmen Shan (Huang et al., 2003; Weller et al., 2013), (ii) Mid-Late Triassic shortening (237-208 Ma) as dated by muscovite $^{40}Ar/^{39}Ar$ ages of early Paleozoic schistose rocks from the northern Longmen Shan (Yan et al., 2011), and (iii) Late Triassic formation of the foreland basin system in the Sichuan Basin (Guo et al., 1996; Li et al., 2003). The second phase of Late Cretaceous – Early Paleogene deformation is characterized by contemporaneous hinterland-ward shearing and foreland-ward thrusting at the back and front sides of the Longmen Shan thrust belt, based on structural mapping and synkinematic mica $^{40}Ar/^{39}Ar$ geochronological analyses (Tian *et al*., 2016). The last phase of deformation occurred in the Late Cenozoic, during which pre-existing structures were reactivated by the eastward growth of the Tibetan Plateau (e.g. Wang *et al*., 2012a; Tian *et al*., 2013).

Songpan-Ganze terrane

The Songpan-Ganze terrane currently forms a triangular fold belt wedged between the North China Block, Yangtze Block, and Qaidam Block (Fig. 1). More than 80% of the Songpan-Ganze terrane is covered by thick Triassic turbidites, which were mainly sourced from the Qinling-Dabie orogen to the northeast and terranes to the north (Enkelmann *et al*., 2007; Weislogel et al., 2010; Ding *et al*., 2013). By latest Triassic, the Songpan - Ganze basin had shallowed, recorded by coeval coal-bearing clastic deposits (BGMRSP, 1991; Chang, 2000). In response to closure of the paleo-Tethys Ocean the flysch basin evolved into a fold belt during Late Triassic time (Xu *et al*., 1992; Roger *et al*., 2011). Jurassic – Cenozoic deposits, have been recently reported in the western part of the terrane (Ding *et al*., 2013).

The Songpan-Ganze terrane was intruded by Late Triassic–Jurassic granitoids (Roger *et al*., 2011), with emplacement ages in the range 228 - 153 Ma (Roger, *et al.*, 2004; Zhang, *et al.*, 2006; Xiao, *et al.*, 2007; Zhang, *et al.*, 2007; Weislogel, 2008; Yuan, *et al.*, 2010). Metamorphic overprinting is relatively strong along the terrane margins where mudstones were metamorphosed to phyllite, but weak within the basin interior (Chang, 2000).

PREVIOUS DETRITAL ZIRCON STUDIES

Over the past decade, the provenance of the Late Triassic clastic sediments in the Sichuan Basin has been intensively studied, especially by detrital zircon geochronology (Fig. 1), but this has led to conflicting conclusions. Deng *et al*. (2008) reported ages of four Late Triassic sandstone samples from the western Sichuan Basin and the eastern Songpan-Ganze terrane, and suggested that the Late Triassic Xujiahe Formation was sourced from the Songpan-Ganze terrane and Longmen Shan thrust belt. By contrast the study of Chen (2011) based in the northern and western parts of the Sichuan Basin indicated that the Qinling orogen to the north was the main source of sediments. Recently work by Luo *et al*. (2014), Zhang *et al*. (2015a) and Shao *et al*. (2016), suggest that the Longmen Shan thrust belt and the Songpan-Ganze terrane in the west and the Qinling-Dabie orogen in the north were the source of the Late Triassic sediments in the western and northern Sichuan Basin, respectively. Zhang *et al*. (2015a) and Shao *et al*. (2016) also indicated the minor role of the north Yangtze Block in supplying sediments to the northern Sichuan Basin. Shao *et al*. (2016) suggested that sediments of the western, southern and eastern parts of basin shared the same sources that include the Qinling orogen, southern North China Block, the eastern Songpan-Ganze terrane and the Longmen Shan thrust belt. Zhu *et al*. (2017) reported detrital zircon ages of four Middle-Late Triassic sandstone samples from the southwestern Sichuan Basin, and suggested that Middle Triassic sediments mainly sourced from the Kangdian basement and Emeishan Large Igneous Province to the south, whereas Late Triassic sediments came mainly from the Songpan-Ganze terrane and Yidun arc to the west with a minor component from the Qinling orogen to the north and Jiangnan Xuefeng thrust belt (southeastern Yangtze Block) to the east. Importantly, most of these previous studies focused on the Late Triassic; little is known about the source of the Early Triassic clastic rocks. A core aim of this study therefore, is to try and resolve the ongoing debate about the sources of the Triassic sediments.

SAMPLING AND ANALYTICAL METHODS

Samples were collected from the Longcanggou, Longmendong and Chuanzhu sections in the southwestern part of the Sichuan Basin. These sections expose all Triassic formations (Figs 5 and 6). Details of the stratigraphy and sedimentology for each sections is provided in the supplementary text. Samples include two sandstones from the Early Triassic Feixianguan (T_1f) and Jialingjiang Formation (T_1j), one volcanic tuff sample from the boundary between the Jialingjiang Formation (T_1j) and Leikoupo (T_2l), two sandstones from the Middle Triassic Leikoupo Formation (T_2l) and five sandstones from the Upper Triassic Maantang (T_3m) Xiaotangzi (T_3xt) and Xujiahe Formations (T_3x) (Figs 5 and 6).

Paleocurrent measurments were made based on cross-bedding and ripples in sandstone beds. The orientations of trough cross laminations were measured using the method described by DeCelles *et al*.

(1983). Eighteen sandstones with no evident diagenetic alteration were selected from three sections (Fig. 6) and were point counted using photomicrographs following the Gazzi-Dickinson method (Dickinson et al., 1983). The statistics are presented in supplementary tables 1.

Ten samples were selected for detrital zircon U-Pb analysis. Analyses were made by LA-ICP-MS using the facilities at the London Geochronology Centre, University College London, based on a New Wave NWR193 excimer laser ablation system and an Agilent 7700x quadrupole mass spectrometer. The laser was set to produce ~2.5 J/cm^2 energy density at 8 Hz repetition rate for 25 seconds. The spot diameter was set to 25 μm for all analyses. Repeated measurements of internal U/Pb age standard Plešovice [TIMS reference age of 337.13 ± 0.37 Ma (Sláma *et al*., 2008)] and NIST-610 silicate glass (Jochum *et al*., 2011) were used to correct for instrumental mass bias and laser-pit-depth-dependent isotopic fractionation. GJ-1 (Jackson *et al*., 2004) and 91500 zircon (Wiedenbeck *et al*., 2004) were used as external standards. In generalm 100 or more single grain ages were collected for each sample. Data reduction was processed using the GLITTER software package (Griffin *et al*., 2008).

RESULTS

Paleocurrent

Paleocurrent data were collected from 7 sites, as summarized in the Fig. 2. The paleocurrent in the Feixianguan Formation, measured in the Longcanggou section (L01), is eastward (Fig. 5). The results, derived from cross-bedding and current ripples in sandstone in the Longcanggou (L02), Chuanzhu (C01, C02) and Hanyuan areas (YD01, SQ02, HY01), indicates an eastward and southeastward paleocurrent direction for the Xiaotangzi and Xujiahe Formations (Fig. 5).

Sandstone petrology

The Early Triassic sandstones are texturally immature, with poor sorting sand (Fig. 5). Sandstones from Early Triassic Feixianguan and Jialingjiang Formation (Fig.6) are quartzo-feldspatho-litho to feldspatho-quartzose-litho sedimentaclastic (classification after Garzanti (2016)) (Figure 5f). Seven samples from the Longcanggou and Longmendong sections yield an average composition QFL = 23:25:52 (Fig. 7a). Quartz grains are generally monocrystalline and subangular to subrounded (Figure 5f). Feldspars range from 19% to 30% and are altered. Lithic fragment compositions are 30% metamorphic, 32% volcanic and 38% sedimentary (Fig. 7b). Volcanic grains are mainly basaltic debris.

Sandstones from the Middle Triassic Leikoupo Formation are feldspatho-litho-quartzose to litho-feldspatho-quartzose (average composition QFL = 81:8:11, LmLvLs = 29:17:51) (Figs. 5g, 7a). Quartz grains are mainly monocrystalline (74%) with considerably polycrystalline (7%). Lithic fragments are mainly siltstone, with minor chert, quartzite, schist, and basaltic debris.

Sandstones from the Late Triassic (Fig. 6) are mainly litho-quartzose (average composition QFL = 74:7:19, LmLvLs = 27:9:64) (Figs. 5h, 5i, 5j, 7). Quartz grains are mainly monocrystalline (69%) with considerably polycrystalline (5%). Lithic fragments are mainly siltstone and slate, with minor chert, limestone, quartzite, schist, and volcanic.

Zircon U-Pb isotopic results

In total, 1132 detrital zircons from nine detrital samples were analyzed. The U–Pb data for each sample are presented in supplementary tables 2-3. As with convention, we only consider U-Pb ages that were no more than 15% discordant or 5% reverse discordant (e.g., Rittner et al., 2016). The age distributions are displayed as kernel density estimate (KDE, Vermeesch, 2012) plots.

Altered tuff

Sample SZ02 (102°51′42.92″ E, 29°40′47.12″N) of the altered tuff was collected from the boundary between the Leikoupo and the underlying Jialingjiang Formations in the Longcanggou section. Some 30 out of 34 analyses yielded concordant ages most of which define a weighted mean $^{206}Pb/^{238}Pb$ age of 246.5 ±1.7 Ma (n=26) (Fig. 8), which is similar to previous studies at other sites of the Yangtze Block, hundreds of kilometers away from our study area (Ovtcharova *et al*., 2006; Xie *et al*., 2013; Lehrmann *et al*., 2015). This new result provides an independent age constraint for deposition of the Triassic strata studied in this work. The raw data and calculated dates are presented in supplementary Table 2.

Early Triassic Feixianguan and Jialingjiang Formations

Sample LCG01 (102°51′42.92″ E, 29°40′47.12″N), a grey-green fine-grained sandstone, was collected from the Feixianguan Formation in the Longcanggou section (Fig. 6). Ninety-nine of 156 analyses yielded concordant ages, which range from ca. 243±3 Ma to 2.4 Ga. The KDE plot of this sample shows a major peak at ~800 Ma (34%), and three minor peaks at ~248 Ma (8%), ~510 Ma (14%) and ~950 Ma (19%) (Fig. 9a).

Sample LMD02 (103°25′5.73″ E, 29°34′46.76″N), a grey-purple coarse sandstone, was collected from the Jialingjiang Formation in the Longmendong section (Fig. 6). Of 129 analyses, 123 yielded concordant ages. Nearly all ages are between 730 - 880 Ma, showing a dominant peak at ~800 Ma in the KDE plot (Fig. 9b).

Middle Triassic Leikoupo Formation

Two samples (grey coarse-grained sandstone), LCG03 (102°51′35.19″ E, 29°40′51.35″N) and LCG04 (102°51′35.05″ E, 29°40′51.18″N), were collected from the Leikoupo Formation exposed at the Longcanggou section (Fig. 6). One hundred and thirty-six out of the 153 zircon grains analysed gave concordant ages that ranged from ca. 242±3 Ma to 2.5 Ga, with 74% lying between 730 Ma and 880 Ma, showing a dominant mode at ~800 Ma (Fig. 9c), similar to the lower sample LMD02 from the Jialingjiang Formation.

One hundred and fifty-two out of 157 zircon grains analysed in sample LCG04 were concordant. Ages exhibit a wide range from ca. 233±3 Ma to 3.0 Ga; but most fall between 230 Ma to 1050 Ma (89%). A KDE plot of the data shows a main peak at ~800 Ma (49%), and three minor peaks at ~248 Ma (5%), ~510 Ma (7%) and ~950 Ma (14%) (Fig. 9d).

Late Triassic Maantang, Xiaotangzi and Xujiahe Formations

Two samples (grey sandstone), LCG05 (102°51′34.05″E, 29°40′51.18″N) and LCG06 (102°51′34.05″E, 29°40′51.18″N), were collected from the Maantang Formation and the upper part of Xujiahe Formation in the Longcanggou section (Fig. 6). For sample LCG05 149 out of 154 single zircon ages of are concordant. Most ages cluster at ~1800 Ma, with minor peaks at ~250 Ma, ~800 Ma and ~2500 Ma (Fig. 9e). The age distributions are significantly different from the lower ones (Figs 9a-d). Late Triassic sample LCG06 yielded 99 concordant ages out of 110 analyses. The KDE plot shows five peaks at ~246 Ma, ~440 Ma, ~758 Ma, ~1870 Ma and ~2480 Ma, respectively (Fig. 9f).

Three samples (grey sandstone), CZ05 (103°24′6″E, 29°37′23″N), CZ01 (103°24′22″E, 29°37′20″N), and CZ03 (103°24′43.2″E, 29°37′27″N), were collected from the upper part of the Xiaotangzi and Xujiahe Formations in the Chuanzhu section (Fig. 6). The KDE plots of these samples are similar, showing peaks at ~276 Ma, ~429 Ma, ~1030 Ma, ~1860 Ma and ~2470 Ma (Figs 9g-i).

DISCUSSION

Detrital sources

Zircon spectra of potential sources

As suggested by previous detrital zircon studies of the Sichuan Basin (Deng *et al*., 2008; Weislogel *et al*., 2010; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015a; Shao *et al*., 2016; Zhu *et al*., 2017), potential source terrains for the Triassic strata include the eastern Songpan-Ganze terrane, northern and southern Kangdian, Longmen Shan thrust belt, Qinling orogen, southeastern Yangtze Block. To facilitate comparison, we compiled zircon U-Pb ages of the pre-late Triassic crystalline and clastic rocks exposed in these potential source areas (Fig. 10). The detrital zircon U-Pb age spectrum of the eastern Songpan-Ganze terrane shows three major peaks at ~290 Ma, ~ 430 Ma, ~1870 Ma, and two minor peaks at ~770 Ma, ~950 Ma, ~2480 Ma (Fig. 10f). The northern and the southern Kangdian basement is characterised by different zircon U-Pb age spectra, with the northern part including two major peaks at ~800 Ma and ~930 Ma and a minor peak at ~260 Ma (Fig. 10g), and the southern part composed of multiple peaks at ~810 Ma, ~1840 Ma, ~2310 Ma and ~2430 Ma (Fig. 10h). The Longmen Shan thrust belt produces three major peaks at ~520 Ma, ~750 Ma and, ~945 Ma (Fig. 10i). The Qinling orogen is characterised by three major peaks at ~440 Ma, ~815 Ma and ~1995 Ma, and three minor peaks at ~260 Ma, ~1830 Ma and ~2465 Ma (Fig. 10j). The southeastern Yangtze Block yields a dominant peak at ~815 Ma (Fig. 10k).

It is worth noting that ratios between components of the age spectra of potential source areas may not be representative, even though hundreds of single ages have been compiled. This is because the spectra are based on only a small number of studies of Neoproterozoic sediments, covering a small part of the source area (Figs 10g, i and j). For example, the age data of north Kangdian basement are mostly (336 out of 407 U-Pb ages) derived from the Neoproterozoic Yanbian Group (Zhou *et al*., 2006a and Sun *et al*., 2009), and 37 of the 407 dates are ~800 Ma crystallization ages of Neoproterozoic igneous rocks, (Fig. 10g). The remaining 34 dates come from an Upper Permian sandstone sample of ~260 Ma, likely derived from Emeishan igneous province (He *et al*., 2007). Our data interpretation ignores the proportions of age peaks as these will be affected by zircon fertility and variations in exposure area of the different rock types across the study area.

Detrital sources of the Early and Middle Triassic strata

Detrital zircon age of four Early and Middle Triassic samples (LCG01, LMD02, LCG03, LCG04) defines a prominent peak at ~810 Ma. It is worth noting that two of four samples (LCG01, LCG04) exhibit three minor peaks at ~255 Ma, ~535 Ma and ~970 Ma, which are absent from samples LCG 02 and LMD02 (Fig. 9).

The ~810 Ma age peak is present in three potential source areas; the northern Kangdian basement, the southeastern Yangtze Block and the Longmen Shan. The most likely source is the northern Kangdian basement. The age spectra of crystalline rocks of the northern Kangdian basement is dominated by the peak at ~800 Ma, similar to that of Early and Middle Triassic sediments. However, the bulk age spectra of the northern Kangdian basement also includes a major peak at ~930 Ma, which forms a minor component in the Early and Middle Triassic sediments. This suggests the Neoproterozoic meta-sediments of the northern Kangdian were not a major source, probably because exposure of meta-sediments is relatively limited.

The southeastern Yangtze Block cannot be ruled out as a possible source for Early and Middle Triassic sediments; but the possibility is very low. If the southeastern Yangtze Block were a source, it would require a long drainage system to deliver the sediments into the southwestern Sichuan Basin via the northern Kangdian, because the southeastern Yangtze Block and the southwestern Sichuan Basin were separated by a N-S striking depocenter, running across the central part of the basin (Figs. 4b, c), where coeval deposits are composed of carbonate, shale and mudstone (Hu, *et al.*, 2010; Tan, *et al.*, 2014; Sun, *et al.*, 2015).

The ~810 Ma age mode might also be sourced from the Longmen Shan, even though it does not form a major age peak therein (Fig. 10i). This interpretation is also supported by the presence of a minor age peak at ~535 Ma in both the Paleozoic sedimentary rocks of the Longmen Shan and the Early and Middle Triassic strata in the study area (Figs 10a, i). Such an interpretation in terms of the source area is also consistent with the eastward paleocurrent directions of these Early and Middle Triassic sediments (Fig. 5).

Further, our Early and Middle Triassic samples also shows a minor peak at ~255 Ma, which overlaps with the age of the Emeishan basalt (~260 Ma) (He *et al*, 2007), which is widespread in the northern Kangdian basement region (Fig. 1). This result supports our interpretation that the Kangdian basement was a major source for the southwestern Sichuan Basin. The ~255 Ma peak is minor, probably because of the relatively lower concentration and relatively small grain-size of zircons in mafic rocks.

Last but not least, the above interpretation is also supported by the relatively higher content of volcanic detritus and the relatively more complex lithic composition in Early Triassic formations (average 32% of total lithic grains) (Fig. 7). The most likely source of the volcanic clasts is the Emeishan large igneous province, located south of the Sichuan Basin. The complex lithic composition may result from the multiple rock types in that region, where metamorphic (slate, phyllite), volcanic (basalt, rhyolite, andesite, granite) and sedimentary (limestone, dolomite, shale, mudstone, siltite, sandstone, conglomerate) rocks were preserved (BGMRSP, 1991).

Detrital sources of the Late Triassic strata

In contrast to the Early-Middle Triassic samples, detrital zircons from the Late Triassic samples (LCG05, LCG06, CZ05, CZ01, CZ03), which exhibit southeastward paleocurrent directions (Fig. 5), give multiple age peaks at ~270 Ma, ~435 Ma, ~775Ma and ~1010 Ma, ~1840Ma and 2480 Ma (Fig. 10b). Detrital zircon data of the coeval sediments in the southwestern, western and northern Sichuan Basin, as reported in previous studies, yield similar age spectra (Figs 10c, d, e), indicating that they may shre the same or similar sources, that include the Qinling orogen, Longmen Shan thrust belt, and eastern Songpan-Ganze terrane (Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015a; Shao *et al*., 2016).

Similar age spectra are seen in the Triassic turbidites of the eastern Songpan-Ganze terrane (Weislogel *et al*., 2006, 2010; Enkelmann et al., 2007; Ding *et al*., 2013; Wang et al., 2013a; Zhang et al., 2014, 2015b), that may have shared similar sources as the Sichuan Basin. Alternatively, the eastern Songpan-Ganze terrane may have experienced a phase of shortening in response to the Late Triassic intracontinental orogeny along the Longmen Shan thrust belt (Li *et al*., 2003a; Yan *et al*., 2011; Zheng *et al*., 2016). From this perspective, it is speculated that the eastern Songpan-Ganze terrane might also be a source region for the Late Triassic detritus of the Sichuan Basin.

Therefore, detritus of the southwestern Sichuan Basin probably changed significantly between Early and Late Triassic time switching from the Northern Kangdian basement to the Qinling orogeny - Longmen Shan thrust belt - eastern Songpan-Ganze terrane. Such a change is also supported by the composition change of sandstone from lithic- to quartz-rich (Fig. 7). This change in Triassic sediment routing system has significant palaeogeographic and tectonic implications as discussed below.

Tectonic and palaeogeographic implications

Despite significant change in detrital zircon age spectra, palaeocurrent orientations of the Lower, Middle and Upper Triassic strata barely changed and are mostly eastward. To account for this the Kangdian basement, which is now south of the study area, would need to have been located to the west (Fig. 11a). This requirement, that the basement experienced considerable eastward displacement relative to the Sichuan Basin, is consistent with the Late Mesozoic and Cenozoic deformation history of the region: Migration of Mesozoic depocenters in the Sichuan Basin, Meng *et al* (2005) suggested that the basin experienced considerable clockwise rotation during Mesozoic time, and Late Cenozoic left-lateral strike-slip along the Xianshuihe fault displaced the Kangdian basement eastward from the Longmen Shan by ~80 km (Wang *et al*., 2009; Tian *et al*., 2014).

A conclusion that Late Triassic sediments in the Sichuan Basin were mainly sourced from the Qinling orogeny and the Longmen Shan thrust belt is consistent with previous studies (Fig, 11b) (Deng *et al*., 2008; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015; Shao *et al*., 2016; Zhu *et al*., 2017). The sediment routing system is mostly eastward and southeastward, as indicated by the paleocurrent data (Fig. 5). The similarity in detrital zircon age distributions between the Late Triassic sediments and the eastern Songpan-Ganze terrane indicates that the eastern Songpan-Ganze terrane might also have been significantly shortened and unroofed, providing detritus for the western and southern Sichuan Basin. The Late Triassic shortening of the Songpan-Ganze turbidites might relate to several possible processes, including (1) westward subduction of the Ganze–Litang Ocean during the Late Triassic (Hou *et al*., 2004), (2) collision between Yidun arc and the Songpan-Ganze terrane at the end of the Triassic (Hou *et al*., 2004; Wang *et al*., 2013a), (3) intra-continental transpressional shortening between the eastern

Songpan-Ganze terrane and the Sichuan Basin, forming the Longmen Shan thrust belt(e.g. Li *et al*., 2003a; Harrowfield & Wilson, 2005; Wang & Meng, 2008), and (4) slab retreat or rollback of Paleo-Tethys lithosphere (e.g. de Sigoyer *et al*., 2014; Pullen *et al*., 2008; Zhang *et al*., 2015c).

Late Triassic uplift and unroofing of the Longmen Shan thrust belt is required to provide detritus for the Late Triassic deposits, as discussed above. This speculation is consistent with other lines of evidence. First, the presence of klippen of Paleozoic and Precambrian rocks over Triassic sediments in the eastern front of the Longmen Shan thrust belt indicate that these structures were formed during the Late Triassic or later. Second, the oldest U–Th–Pb monazite and Sm–Nd garnet ages (204-190 Ma), derived from metamorphosed rocks in the Danba Antiform, immediately south of the Longmen Shan thrust belt, were interpreted as dating the timing of Barrovian metamorphism associated with deformation (Huang *et al*., 2003; Weller *et al*., 2013). Third, muscovite $^{40}Ar/^{39}Ar$ dating of Early Paleozoic schist and Neoproterozoic Pengguan complex from the northern and middle Longmen Shan yielded ages between 237-208 Ma and 235-226 Ma, respectively, which were interpreted as minimum age constraints for Mesozoic crustal shortening (Yan *et al*., 2011; Zheng *et al*., 2016).

As indicated by our palaeocurrent and detrital zircon results, the northern Kangdian basement was uplifted and unroofed to provide the detritus for the Early and Middle Triassic sediments in the southwestern Sichuan Basin (Fig. 11a). However, in Late Triassic time, the basement subsided significantly in Late Triassic time (Fig. 11b), as indicated by the presence of Late Triassic sediments (~1 km, Guo *et al*., 1996) over the basement rocks (Fig. 2). Subsidence of the basement might result from eastward shortening and loading of the eastern Songpan-Ganze terrane over the western margin of the Yangtze Block in response to the Late Triassic collision between the Yangtze Block, Yidun arc and Qiangtang terrane along the Ganze-Litang and Jinshajiang sutures (Fig. 11b). This interpretation is also supported by the eastward paleocurrent and the development of a ~1.5-km-thick Late Triassic depocenter in areas south of the sampling sites (i.e. the location of the northern Kangdian basement) (Fig. 4a). Such a tectonic reconstruction differs from previous models, suggesting continuous Late Permian to Jurassic subsidence related to rifting (Luo, 1983; Guo *et al*., 1996), or early Mesozoic transtensional subsidence by strike-slip faulting (Chen *et al*., 1987; He *et al*., 2003; Chen *et al*., 2011).

CONCLUSIONS

Triassic sediments in the southwestern Sichuan Basin record different detrital zircon geochronology signals. Detrital zircon age spectra of Early and Middle Triassic samples are characterized by a dominant age mode at ~810 Ma, with three minor peaks at ~255Ma, ~535Ma and ~970Ma. In contrast to the Early -Middle Triassic samples, detrital zircon spectra of Upper Triassic samples are characterized by multiple age peaks at ~270 Ma, ~435 Ma, ~775Ma and ~1010 Ma, ~1840Ma and ~2480 Ma.

Our data reveal a major change of provenance during the Late Triassic in response to multiple tectonic events. Sediments in the southwestern Sichuan Basin was supplied by highlands of the Yangtze Block (the northern Kangdian basement) during the Early-Middle Triassic passive continental margin stage. During the Late Triassic, the Sichuan Basin was inverted into a foreland basin and the Longmen Shan thrust belt and possibly the eastern Songpan-Ganze terrane was uplifted in response to the closure of the Paleo-Tethys Ocean and intra-continental shortening. Together with the Qinling orogen, they became the main source areas for the southwestern and western Sichuan Basin. The Late

Triassic sediments in the southwestern Sichuan Basin have thus recorded collision and subsequent convergence between the Qiangtang, Yangtze and North China blocks. This study highlights the importance of tectonic events in reorganizing drainage and sediment supply in a foreland basin system.

Further, during the Late Triassic the northern Kangdian basement region was inverted and then switched from an area undergoing uplift and erosion into a region of subsidence, probably due to the eastward shortening and loading of the Songpan-Ganze terrane over the western margin of the Yangtze Block in response to the Late Triassic collision between Yangtze Block, Yidun arc and Qiangtang terrane along the Ganze-Litang and Jinshajiang sutures.

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Figure captions:

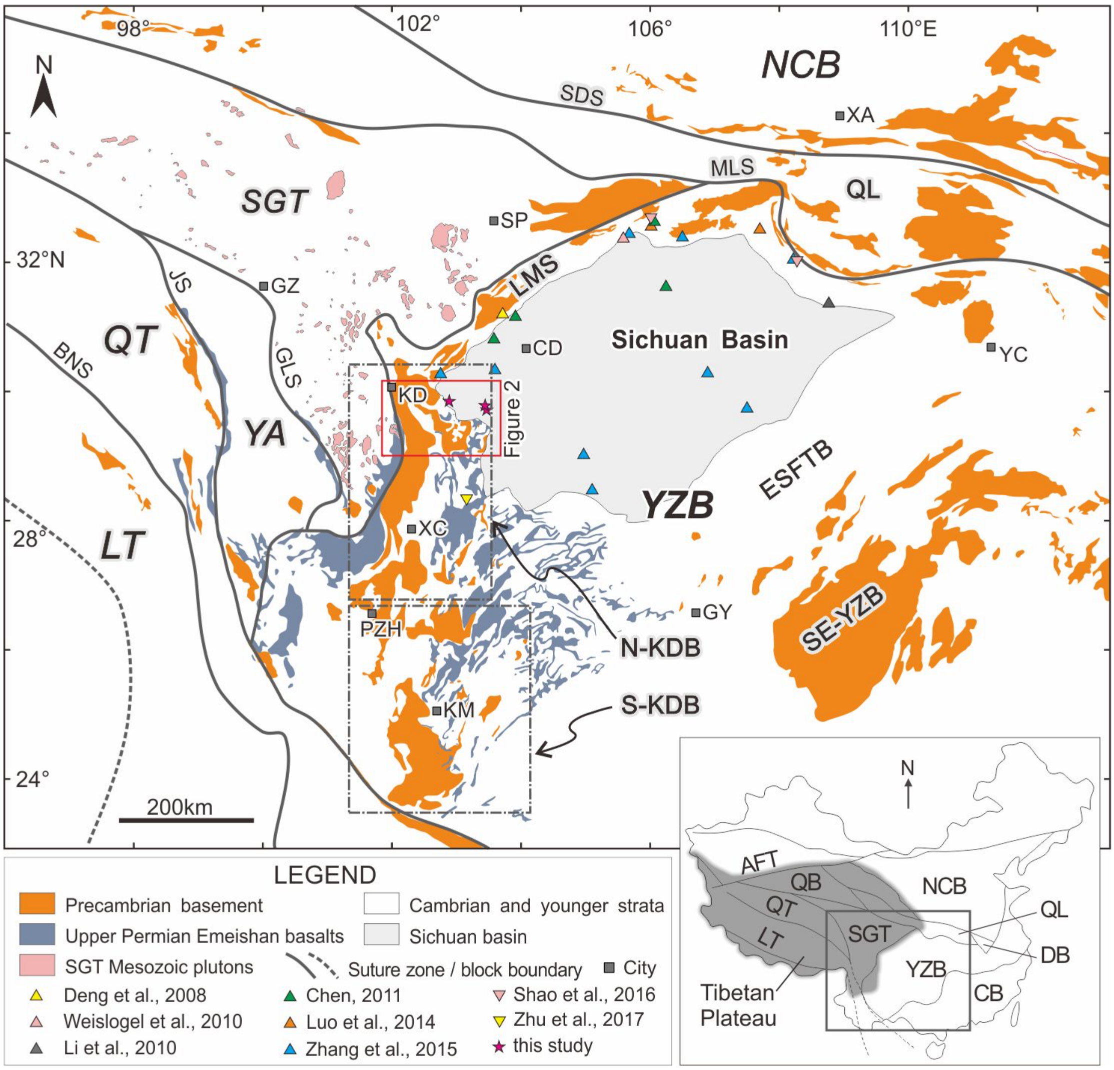

Fig. 1. Simplified tectonic map of the upper Yangtze Block and adjacent regions. Sites of previous detrital zircon geochronology studies of the Sichuan Basin are shown in the figure. Inset shows main tectonic elements of China. ATF, Altyn Tagh fault; CB, Cathaysia Block; CD, Chengdu; DB, Dabie orogen; ESFTB, eastern Sichuan fold-and-thrust belt; GLS, Ganze-Litang suture; GY, Guiyang; GZ, Ganze; JS, Jinshajiang suture; KD, Kangding; KM, Kunming; LMS, Longmen Shan thrust belt; LT, Lhasa terrane; MLS, Mianlue suture; N-KDB, northern Kangdian basement; NCB, North China Block; PZH, Panzhihua; QB, Qaidam Block; QL, Qinling orogen; QT, Qiangtang terrane; S-KDB, southern Kangdian basement; SDS, Shangdan suture; SGT, Songpan-Ganze terrane; SP, Songpan; XA, Xi'an; XC, Xichang; YC, Yichang; YA, Yidun arc; YZB, Yangtze Block. Modified from Tian *et al*. (2012) and Wang & Pan, (2013). The distribution of the Upper Permian Emeishan basalts is modified from Xu *et al*. (2004).

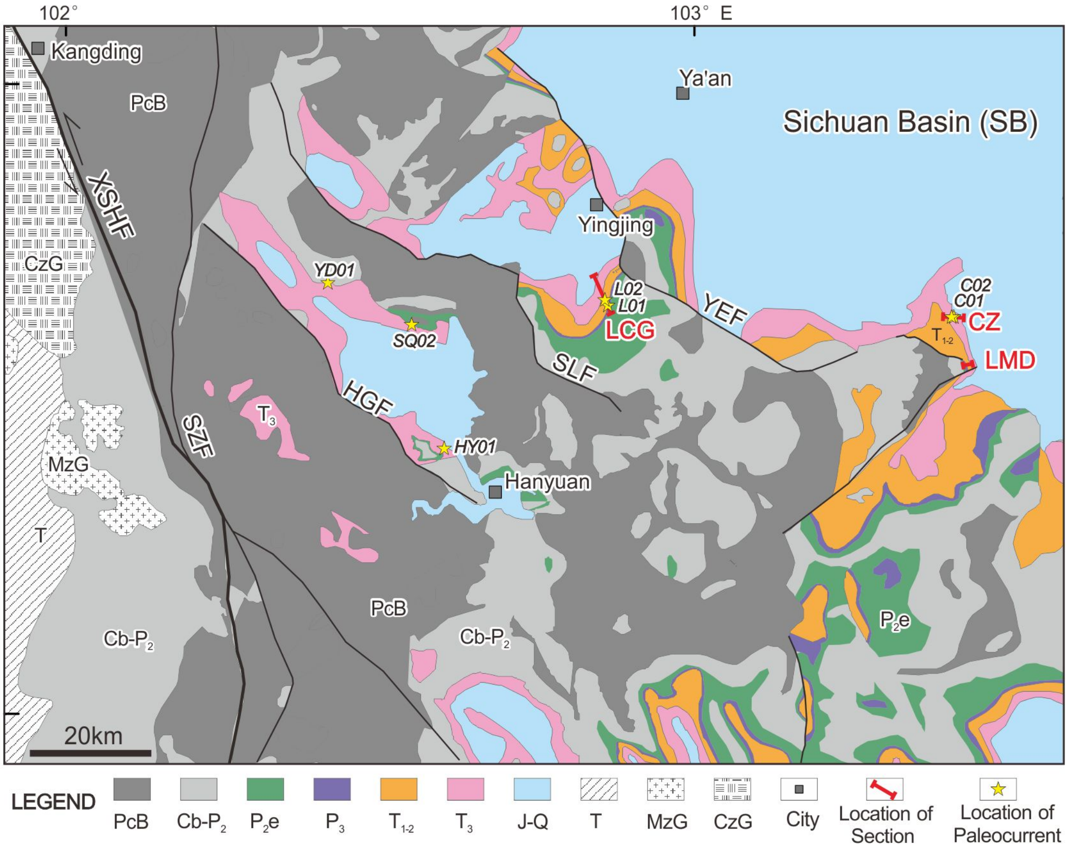

Fig. 2. Generalized geological map of the study area, modified from BGSP (1974). The location of this figure is shown in Fig. 1. Abbreviations: Cb-P_2, Cambrian - Middle Permain; CzG, Cenozoic Granite; HGF, Hanyuan-Ganluo fault; J-Q, Jurassic to Quaternary; MzG, Mesozoic Granite; P_2e, Upper Permain Emeishan basalts; P_3, Upper Permian Xuanwei Formation; PcB, Precambrian basement; SLF, Sanhe-Leibo fault; SZF, Shimian-Zhaojue fault; T, Triassic in the eastern Songpan-Ganze terrane; T_{1-2}, Lower and Middle Triassic; T_3, Upper Triassic; XSHF, Xianshuihe fault; YEF, Yingjing-Emei fault. Red solid lines and text define the localities of the Longcanggou (LCG), Chuanzhu (CZ) and Longmendong (LMD) sections, from which samples were collected.

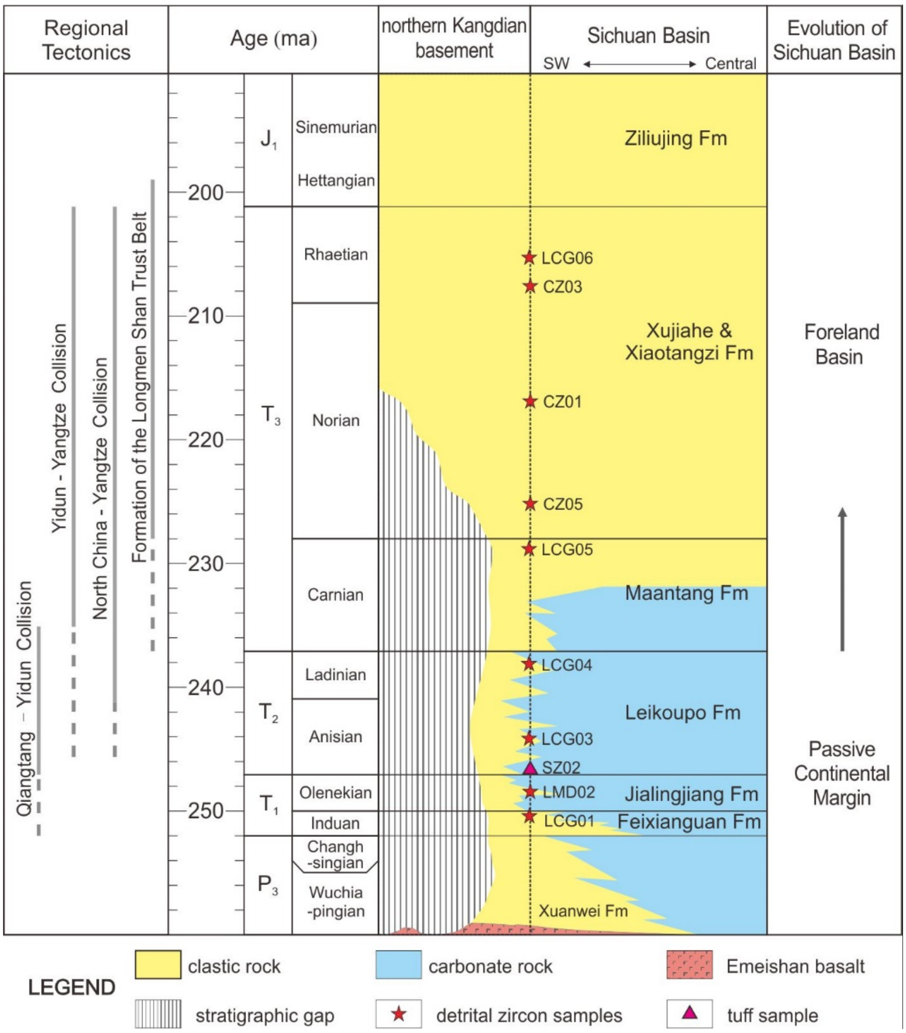

Fig. 3. Stratigraphic nomenclature, age of the southern Sichuan Basin and northern Kangdian Oldland. The time of formation of the Longmen Shan thrust belt is based on Yin (1996); Meng, et al (2005), Li *et al.* (2003a, 2014); the time of North China – Yangtze collision is after Yin & Nie (1993) Zhang *et al*. (1995), Liu *et al*. (2005, 2015); the time of Yidun – Yangtze collision is after Reid *et al*. (2005), Roger *et al*. (2008), Yuan *et al.* (2010), Wang *et al.* (2013a); the time of Qiangtang – Yidun collision is after Reid *et al*. (2005), Pullen *et al*. (2008), Roger *et al*. (2008, 2010). Time scale is from Gradstein *et al*. (2012). J_1, the Early Jurassic; P_3, the Late Permian; T_1, the Early Triassic; T_2, the Middle Triassic; T_3, the Late Triassic.

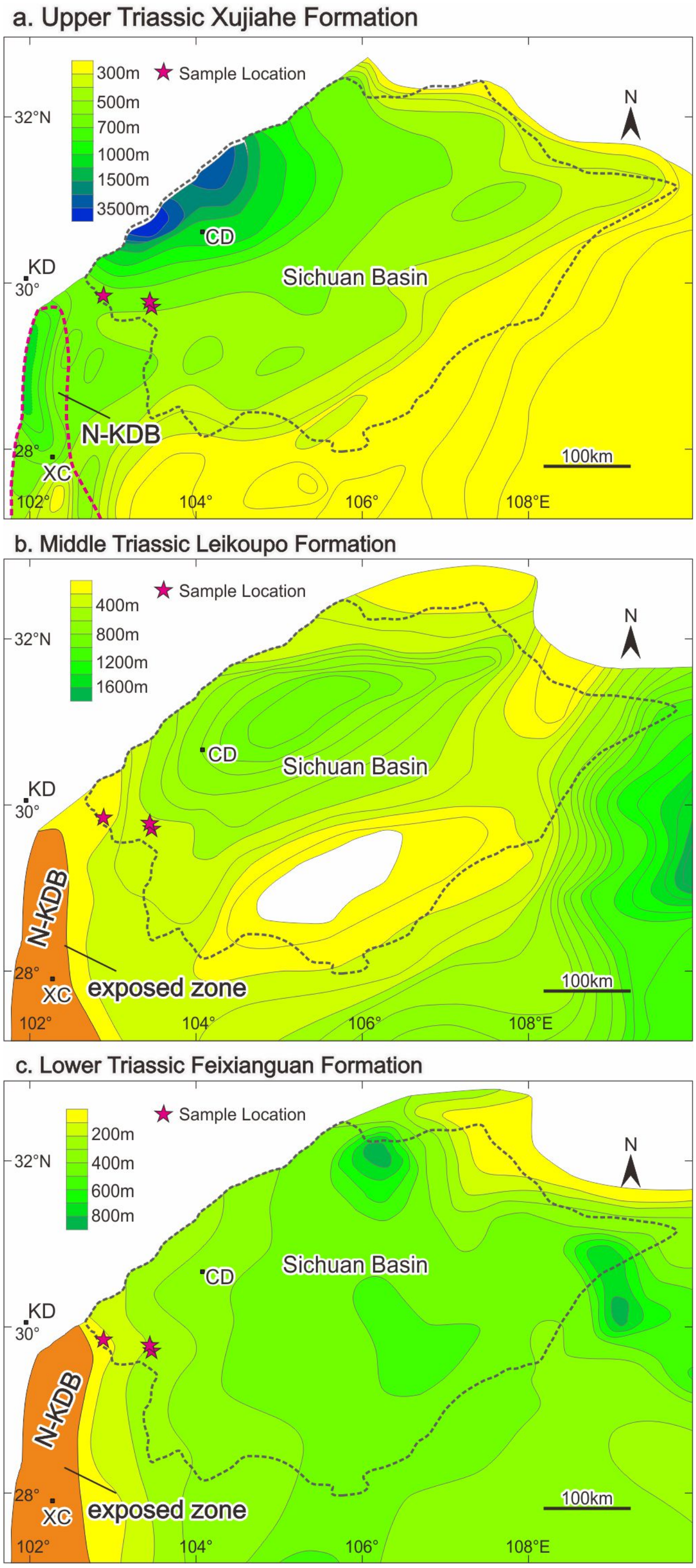

Fig. 4. Isopach maps of the Late Triassic Xujiahe (a), Middle Triassic Leikoupo (b) and Early Triassic Feixianguan (c) Formations in the upper Yangtze Block, including the Sichuan Basin and surrounding regions (modified after Guo *et al*. 1996). Note that yellow patches are exposed parts of northern Kangdian basement. Abbreviations for towns: CD, Chengdu; KD, Kangding; XC, Xichang. Note that in Fig. 4a, the northern Kangdian basement (N-KDB) switched to a depocenter.

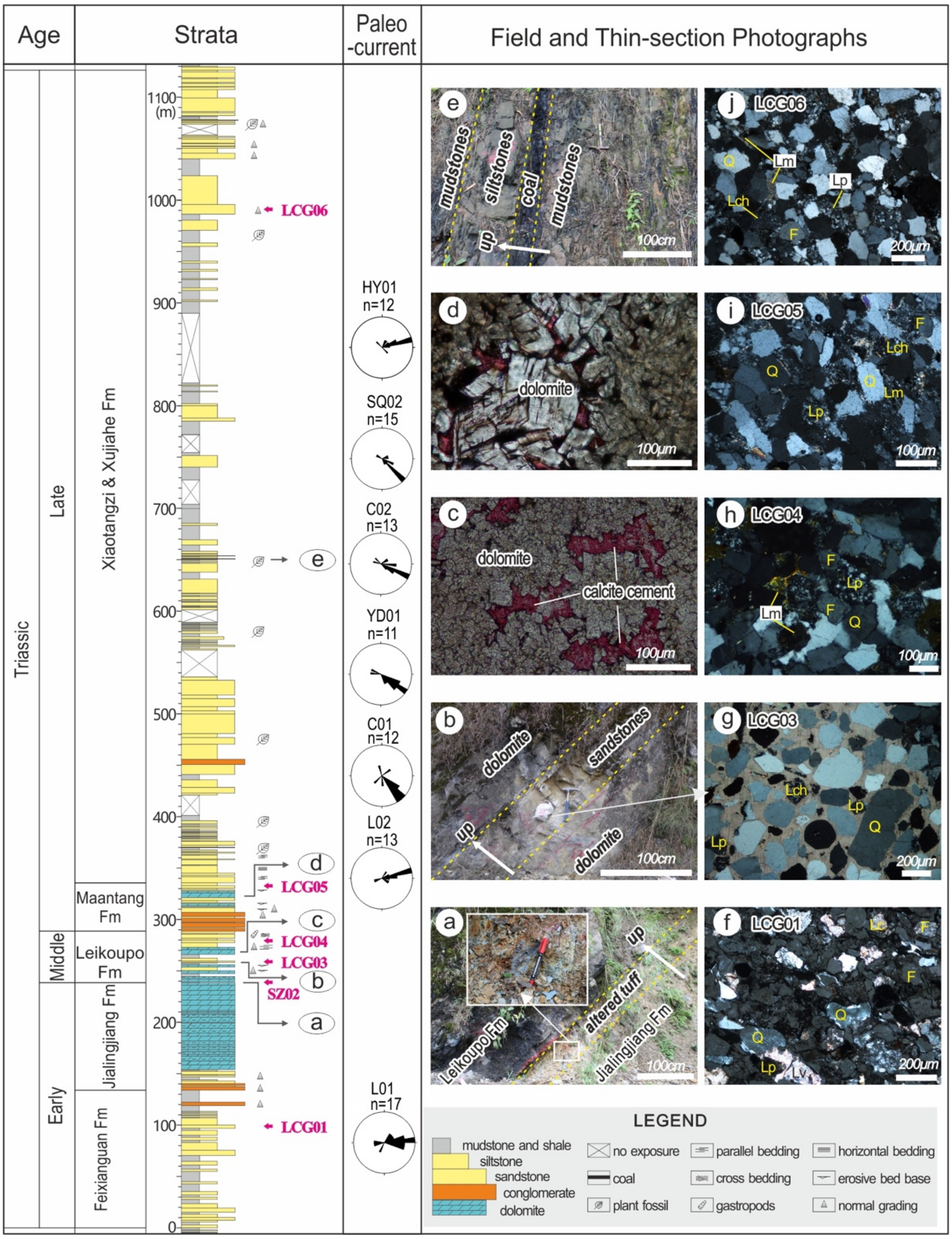

Fig. 5. Stratigraphy, paleocurrent rose diagrams, field photos and thin-section photomicrographs for the Longcanggou section. Locations of paleocurrent measurements are shown in Fig. 2. (a) A field photo showing the boundary (the " altered tuff") between the Early Triassic Jialingjiang Formation and Middle Triassic Leikoupo Formation; (b) Dolomites interbedded between sandstones (sample LCG03); (c) Thin-section photograph of dolomites from the Leikoupo Formation; (d) Dolomites from the upper Mantang Formation; (e) Siltstones and mudstones interbedded with coal from upper part of Xujiahe Formation; (f, g, h, i, and j) Representative photomicrographs of feldspathic (f), quartz-arenitic (g) and lithic sandstones. Abbreviations: F – feldspars, Lch – chert lithics, Lm - metamorphic lithics, Lp - pelite lithics, Q – Quartz.

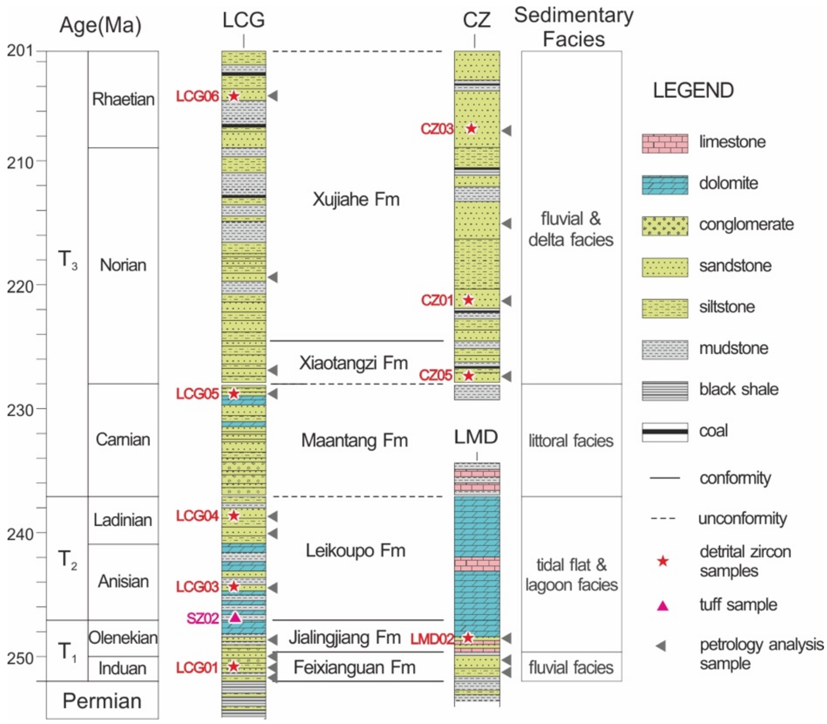

Fig. 6. Comparison of Triassic stratigraphy within the southwestern Sichuan Basin. CZ (Chuanzhu) section is compiled from WGCMSPISB (1984) and LMD (Longmendong) section from Lin *et al*. (1982), Xu *et al*. (1997) and BGMRSP (1997), with the sedimentary facies after Zhao *et al*. (1996). T_1, T_2 and T_3 are the Early, Middle and Late Triassic, respectively. Time scale is from the Gradstein *et al*. (2012), which is consistent with the tuff results derived from the sample SZ02 from the Longcanggou (LCG) section (see Fig. 7).

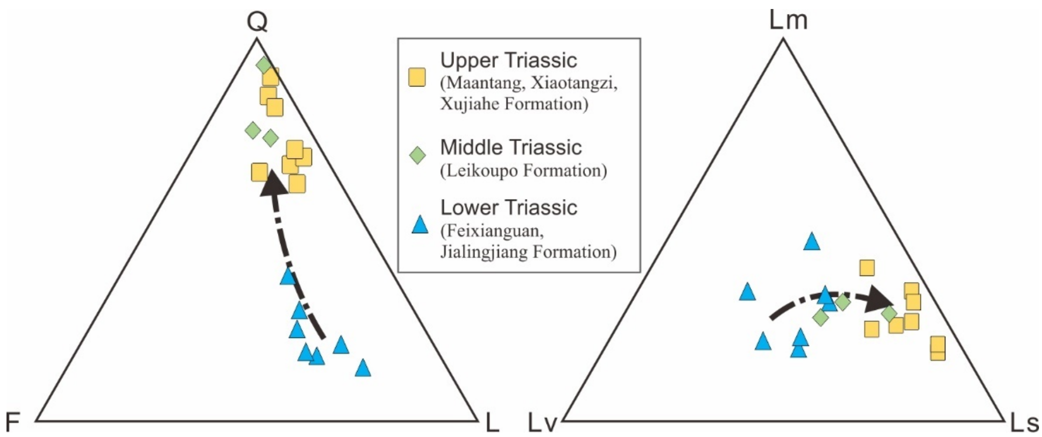

Fig. 7. Ternary diagrams for sandstones of the Lower (Feixianguan and Jialingjiang), Middle (Leikoupo) and Late Triassic (Maantang, Xiaotangzi and Xujiahe) formations. Q, quartz; F, feldspar; L, lithic fragments (Lm, metamorphic; Ls, sedimentary; Lv, volcanic). The black arrows highlight trend of compositional change from lower to upper Triassic deposits.

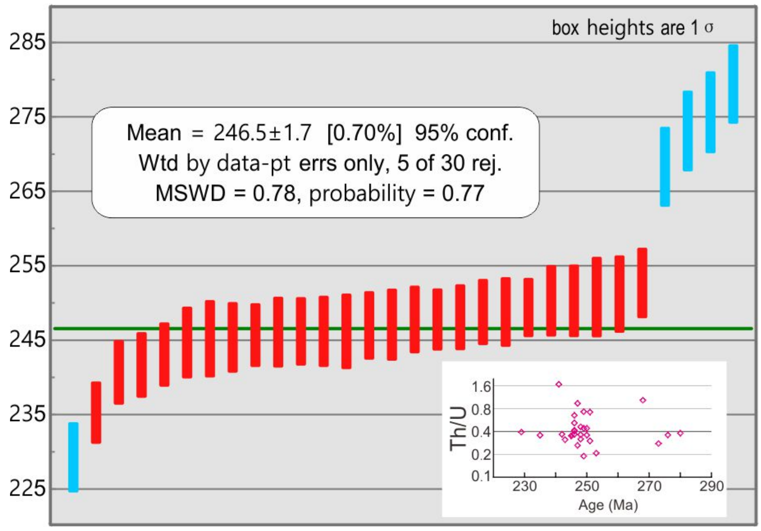

Fig. 8. U–Pb zircon ages from altered tuff sample SZ02. Blue dates are outliers rejected by ISOPLOT for calculating the weighted mean age.

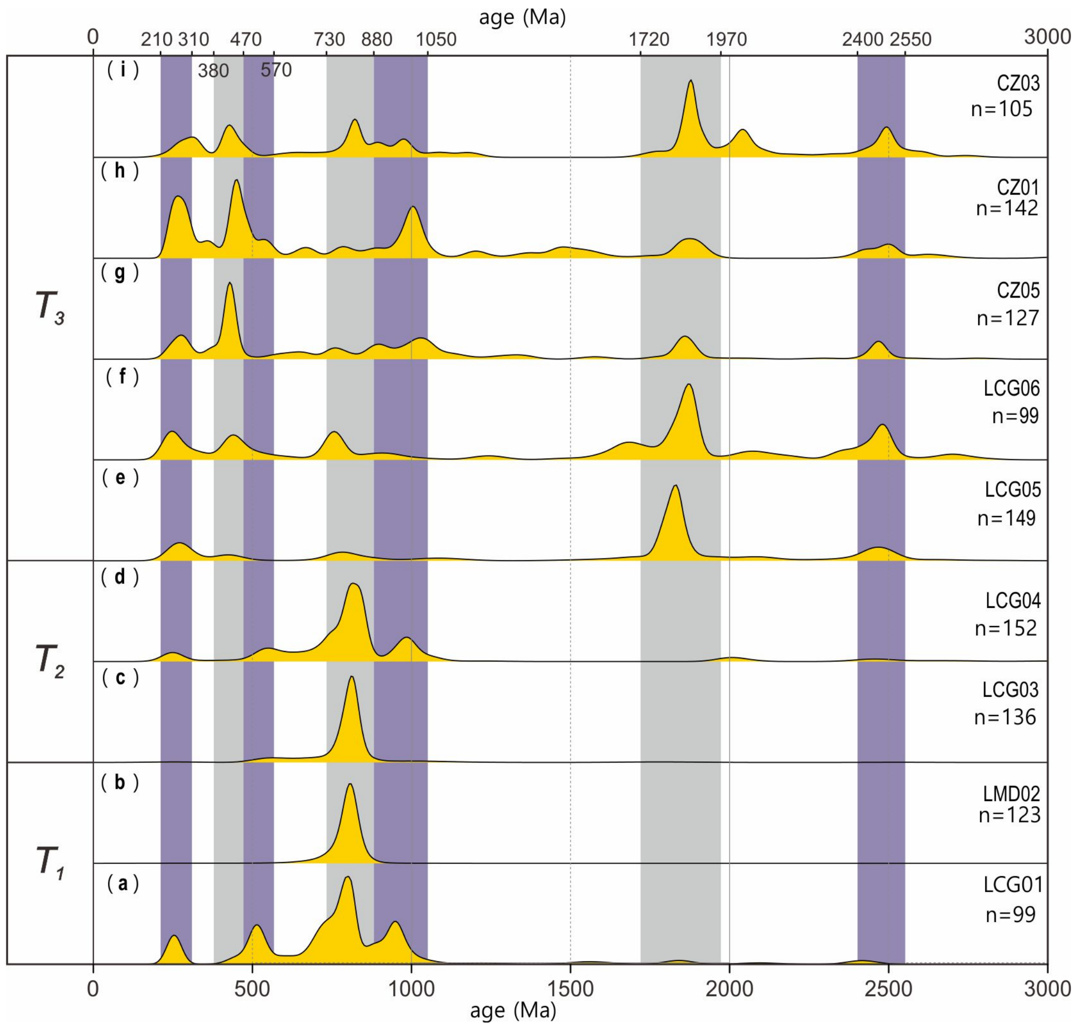

Fig. 9. Kernel Density Estimation (KDE) plots of the detrital zircon U-Pb data for samples LCG01, LMD02, LCG03, LCG04, LCG05, LCG06, CZ05, CZ01 and CZ03, respectively.

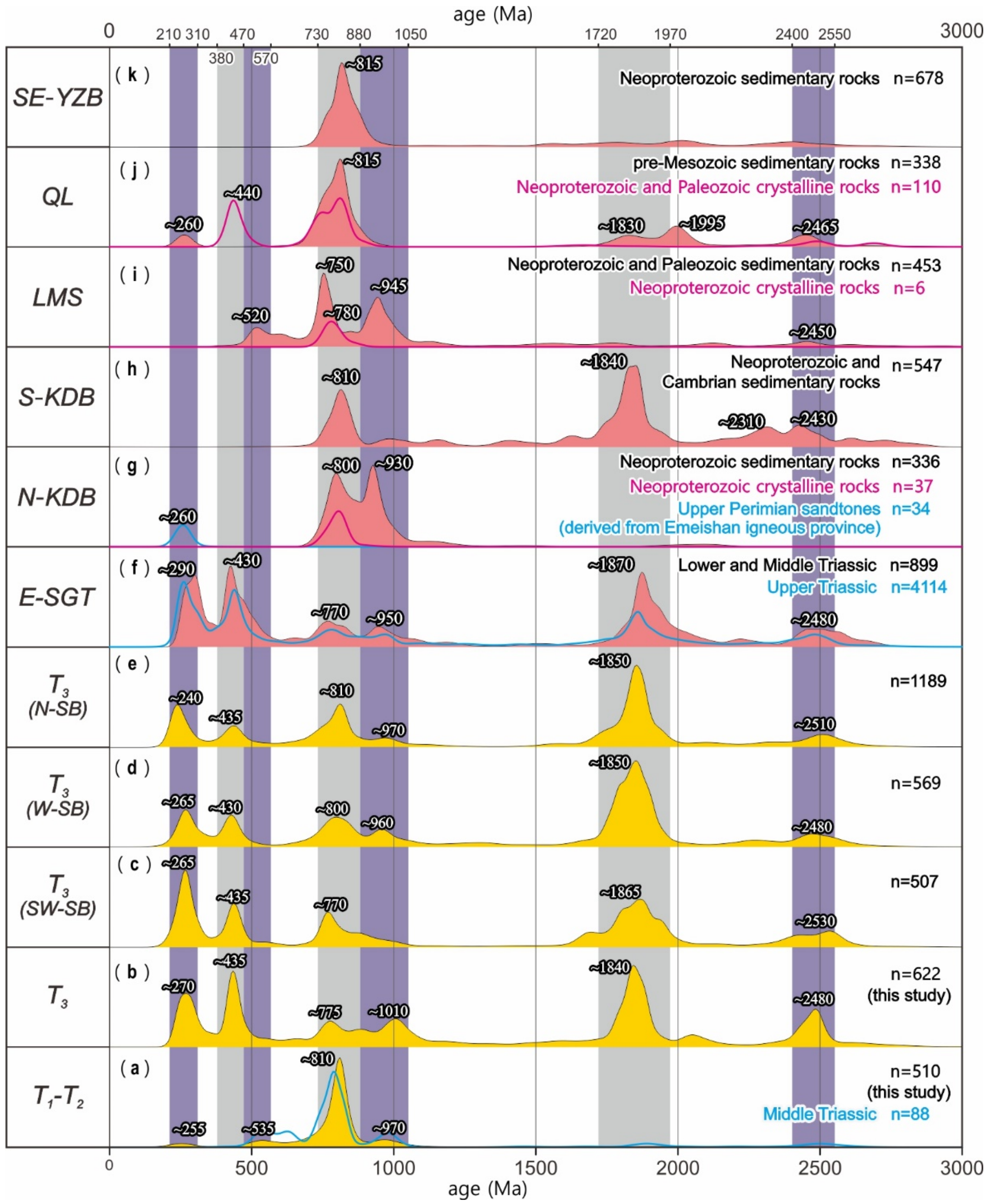

Fig. 10. KDE plots of detrital zircon ages from Triassic sediments in the Sichuan Basin and potential source areas. (a-b) Age spectra of the Early-Middle and Late Triassic sediments in the southwestern Sichuan Basin, Middle Triassic (blue dashline) is after Zhu, et al., 2017. (c-e) Spectra of the Late Triassic sediments in the southwestern, western and northern Sichuan Basin, reported in previous studies (Deng *et al*., 2008; Weislogel *et al*., 2010; Chen, 2011; Luo *et al*., 2014; Zhang *et al*., 2015a; Shao *et al*., 2016; Zhu *et al*., 2017). Spectra of potential areas, including (f) E-SGT (eastern Songpan-Ganze terrane), compiled from the Early-Middle Triassic sedimentary rocks (black solid line) (Weislogel *et al*., 2006, 2010; Enkelmann, 2007; Ding *et al*., 2013; Wang *et al*., 2013a) and the Late Triassic sedimentary rocks (blue dash line) (Wang *et al*, 2007; Weislogel *et al*., 2006, 2010; Ding *et al*., 2013; Wang *et al*., 2013a; Zhang *et al*., 2014, 2015b), (g) N-KDB (northern Kangdian Basement), compiled from both crystalline (red dash line) (Roger & Calassou, 1997; Guo *et al*., 1998; Shen *et al*.,

2000; Li *et al*., 2001; Li *et al*., 2002; Zhou *et al*., 2002; Shen *et al*., 2003; Li *et al*., 2003b; Zhou *et al*., 2006a; Lin *et al*., 2006; Yan *et al*., 2006; Zhao *et al*., 2006; Geng *et al*., 2007; Huang *et al*., 2009; Lin, 2010; Ruan, 2013; Meng *et al*., 2015) and sedimentary rocks (black solid line) (Zhou *et al*., 2006a; He *et al*., 2007; Sun *et al*., 2009), (h) S-KDB (southern Kangdian Basement), compiled from sedimentary rocks (Sun *et al*., 2009; Wang *et al*., 2012b), (i) LMS (Longmen Shan thrust belt), compiled from both crystalline (red dash line) (Zhou *et al*., 2006b; Meng *et al*., 2015) and sedimentary rocks (black solid line) (Duan *et al*., 2011; Chen *et al*., 2016), (j) QL (Qinling orogen), compiled from both crystalline (red dash line) (Li *et al*., 2016 and references therein) and sedimentary rocks (black solid line) (He *et al*., 2007; Wang *et al*., 2013b), (k) SE-YZB (southeastern Yangtze Block), compiled from sedimentary rocks (Wang *et al*., 2010; Wang & Zhou, 2012).

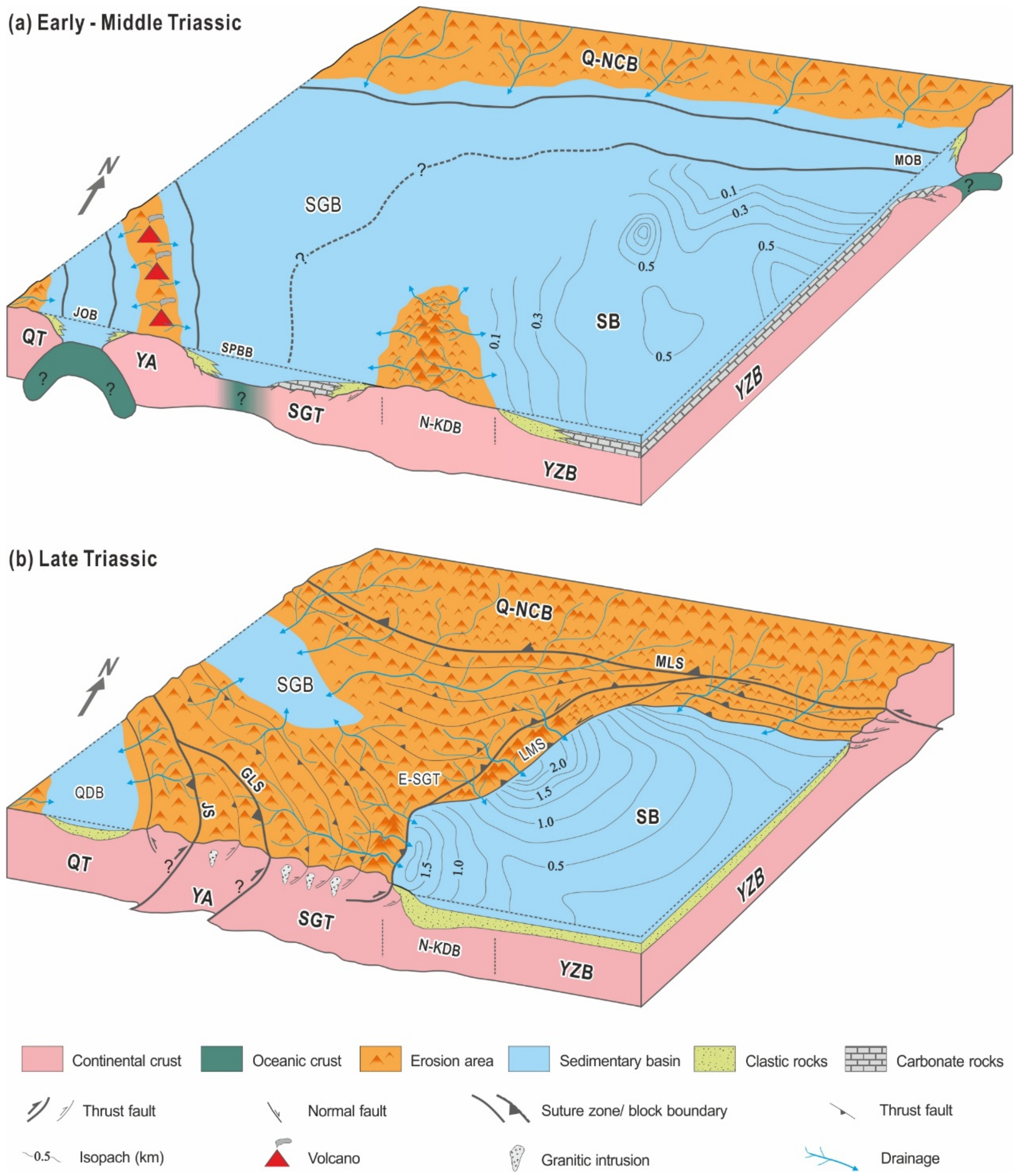

Fig. 11. Models for Triassic tectonic evolution of the upper Yangtze Block and its link to adjacent structural belts. E-SGT, eastern Songpan-Ganze terrane; GLS, Ganze-Litang suture; JOB, Jinshajiang Ocean Basin; JS, Jinshajiang suture; LMS, Longmen Shan thrust belt; MLS, Mianlue suture; MOB, Mianlue Ocean Basin; N-KDO, northern Kangdian basement; QDB, Qamdo Basin; Q-NCB, Qingling Terrane and North China Block; QT, Qiangtang terrane; SB, Sichuan Basin; SGB, Songpan-Ganze Basin; SGT, Songpan-Ganze terrane; SPBB, Songpan back arc Basin; YA, Yidun arc; YZB, Yangtze Block. The tectonic evolution between Qiangtang terrane and northern Kangdian basement is after Roger *et al.* (2008)